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BEAM TRANSPORT IN A COMPACT DIELECTRIC WALL INDUCTION ACCELERATOR SYSTEM FOR PULSED RADIOGRAPHY

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BEAM TRANSPORT IN A COMPACT DIELECTRIC WALL INDUCTION ACCELERATOR SYSTEM FOR PULSED RADIOGRAPHY *

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Abstract

Using dielectric wall accelerator technology, we are developing a compact induction accelerator system primarily intended for pulsed radiography. The accelerator would provide a 2-kA beam with an energy of 8 MeV, for a 20-30 ns flat-top. The design goal is to generate a 2-mm diameter, 10-rad x-ray source. We have a physics design of the system from injector to the x-ray converter. We present the results of injector modeling and PIC simulations of beam transport. We also discuss the predicted spot size and the on-axis x-ray dose.

INTRODUCTION

A dielectric wall accelerator seeks to gain the high-current, high-efficiency advantages of an induction linear accelerator without requiring the substantial real estate (tens of meters) typically needed to achieve a few to tens of MeV of energy. Technological advances such as high-gradient insulators and novel transmission line systems [1] make it possible to build an induction accelerator which is essentially all "gap" with field strengths aproaching 20 MV/m.

We consider here an accelerator with an nominal energy of 8 MeV, and an approximate flat-top duration of 20 to 30 ns. For a nominal 5 inch thick (12.7 cm) stack of gaps totaling 500 kV, the peak field stress in the accelerator region is 3.93 MV/m. The "injector" is not physically distinct from the accelerator itself; it consists of a 10 cm stack of gaps totaling a potential of 1.5 MV, or 15 MV/m. This injector stack plus 13 of the nominal accelerator stacks achieves the desired 8 MV. The cathode size is chosen to produce a nominal 2 kA of beam current.

Beam transport in such a machine has some interesting requirements. Typical induction linacs have sufficient space between accelerating gaps to allow focusing magnets and steering coils to be installed within the cells, providing nearly continuous focusing as well the necessary field structure to "catch" the beam as it emerges from the cathode. For the DWA system, the magnets must be inserted between the accelerating stacks. To achieve nearly continuous focusing without losing real estate, we consider "pancake" magnets with large radial build. Assuming that a single pancake magnet plus the support structure for the cell consumes 2 inches (5.08 cm), we arrive at a total transport distance from cathode surface to exit of 2.42 m, corresponding to an average gradient of 3.3 MV/m. This layout is illustrated in Figure 1.

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Downstream of the accelerator, we consider 3.1 m of discrete magnetic transport to a bremsstrahlung converter target.

MODELING

Simulations of the 8 MV DWA have been performed using the ADCGlib code library developed at LLNL. ADCGlib is an object-oriented C++ library which allows different models appropriate to different parts of the accelerator to be easily connected. In this case, the first 30 cm is modeled using orbit tracking in an RZ geometry, with the proper space charge effects. For optimal beam emittance, one would typically shape the cathode surface, but the high accelerating gradient provided in the injector region allows the use of the flat surface without a major emittance penalty, as will be seen in the Results section.

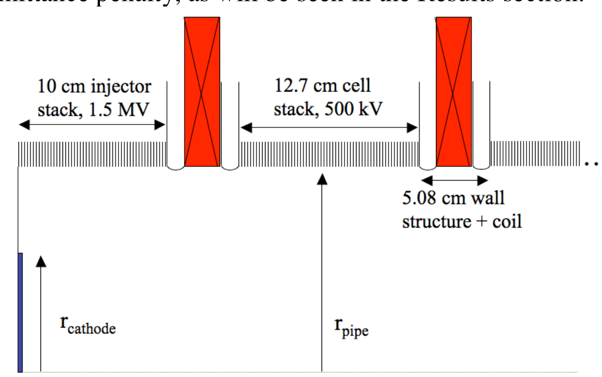

Figure 1: Schematic of cell and magnet layout.

The remaining 2.12 m within the accelerator are modeled with transverse slices, where the first slice is initialized with the same phase space output from the RZ section. Since quadrupole and octopole effects from the transmission line feeds [2] are included in the external fields, the slices (and corresponding field calculations) are not treated as cylindrically symmetric, so that emittance growths from these higher-order fields can be studied. The accelerating field in this region is treated as having a uniform average value that is smoothly matched from the injector region.

Finally, the downstream section is also modeled with transverse slices. The magnetic elements consist of a solenoid to catch the beam as it exits the accelerator, another to match the beam into the final focus lens, and the final focus itself. The length from the final focus midplane to the target plane is 20 cm.

RESULTS FOR BEAM TRANSPORT

We assume that the voltage pulse will not produce a perfect 8 MV for the duration, and will optimize the tune for a slightly lower value of 7.75 MV. To achieve 2 kA this requires a 3 cm cathode radius; the beam pipe has a constant radius throughout the system of 6.6 cm. Typical potential and Ez field structure in the RZ region of the simulation are shown in Figure 2.

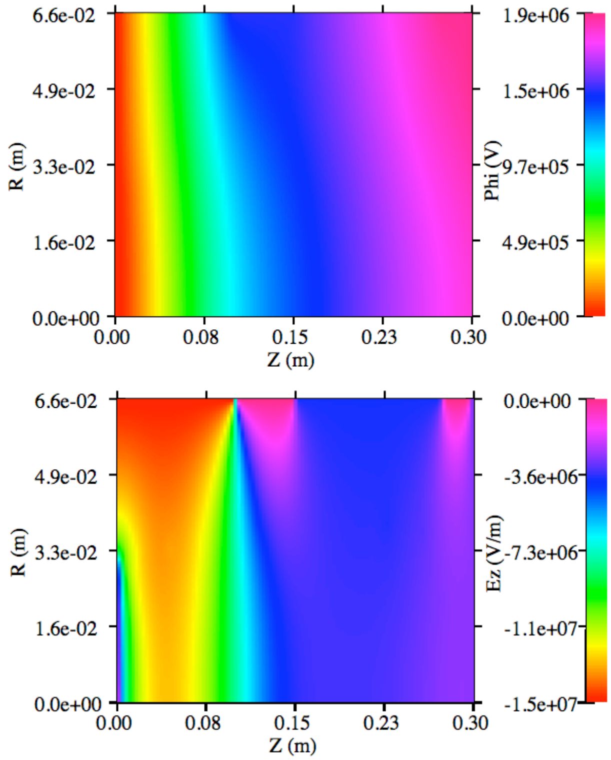

Figure 2: Potential and axial field contours near injector.

The magnetic field profile is given as the sum of pancakes that have a 7.6 cm inner radius, 37.6 cm outer radius, and 2.54 cm thickness, and bucked to zero at the cathode. For the tune shown in Figure 3, we achieve the set of envelopes (as a function of endpoint energy during the voltage pulse) shown in Figure 4; note the desired smooth profile at the nominal 7.75 MV value.

It is worth noting that, while continuous focusing may be desirable for stability reasons [3], the regime of DWA transport is such that no focusing is required at all. We found (but do not show here for lack of space) that by capturing the beam off the cathode with a Pierce column shaping of the injector voltage, the beam could be smoothly transported to the exit with no magnets at all. The initial radial kick supplied by the Pierce column was sufficient; the rate at which the high accelerating gradient "stiffens" the beam is faster than the rate at which space charge or emittance could expand it.

The tune of the downstream transport system is selected to have the least variation of spot size with energy, towards the high end of the range. Note that beam envelope at the exit of the accelerator does not vary wildly above 7.5 MV and so the tune shown in Figure 5 is able to achieve a small spot size, sub-millimeter starting at about 7.25 MV, or an almost 10% range of variation. The profiles are shown in Figure 6 and the RMS spot radius at the accelerator exit and target plane are shown in Figure 7.

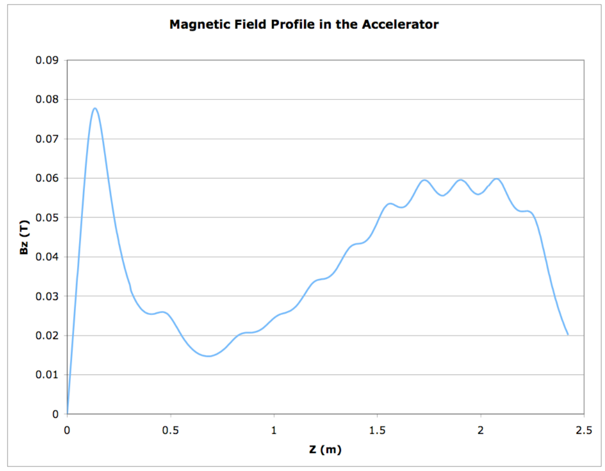

Figure 3: Field profile optimized for 7.75 MV.

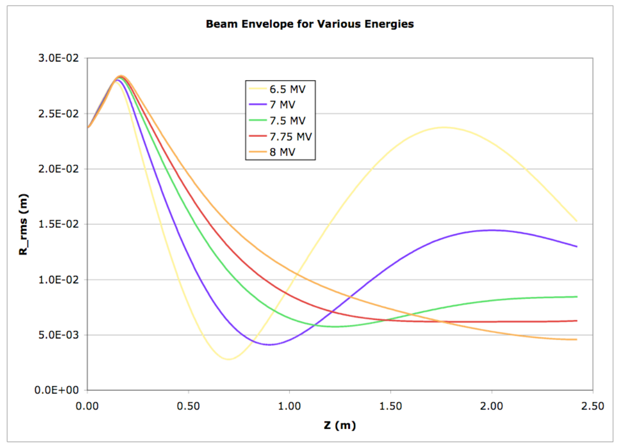

Figure 4: Profiles within the accelerator.

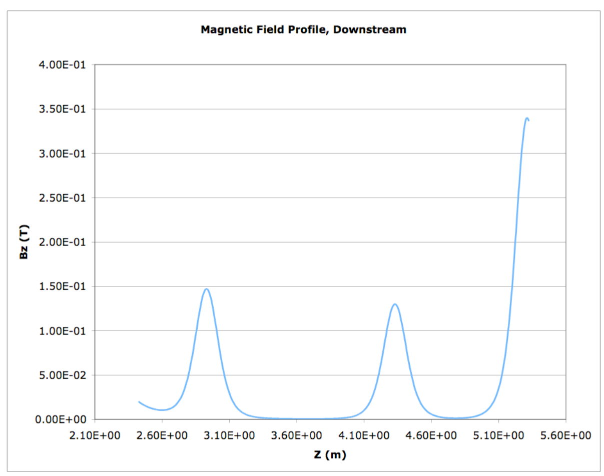

Figure 5: Optimized downstream field profile.

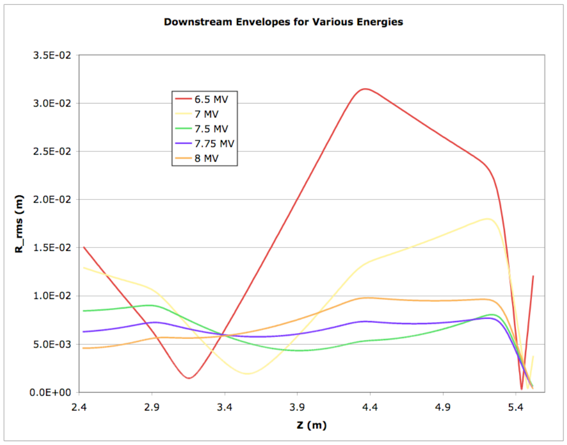

Figure 6: Downstream beam profiles.

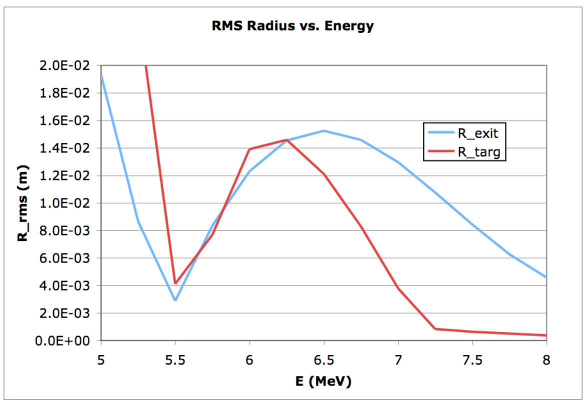

Figure 7: Spot size variation with energy.

Another quantity of considerable interest is the beam emittance. In Figure 8 we showed the normalized Lapostolle value, at both the accelerator exit and at the target plane. Even without shaping the cathode, very acceptable beam quality can be achieved. Note that both this plot and Figure 7 are cut off below 5 MV; in fact, there is a very sharp drop in the beam current transported through the accelerator below 5.5 MV for the nominal tune.

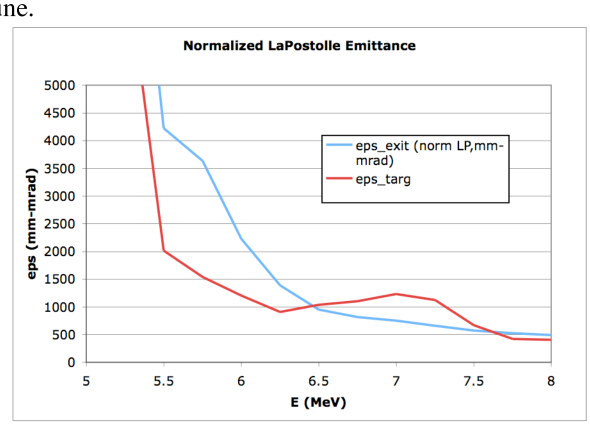

Figure 8: Emittance versus energy for the nominal tune.

RESULTS FOR DOSE

The goal for this DWA concept is to be used as a radiographic source with an output of about 10-20 rad in air at 1 m. The spot size and emittance results from the transport studies were combined with Monte Carlo modeling results for the performance of finite-emittance electron beams [4]. The resulting dose rate versus energy is shown in Figure 9. Note that it folds in the angular spread corresponding to the beam emittance at a given energy, as well as the beam current that is transported at that energy, at the nominal tune. The desired total dose looks quite achievable.

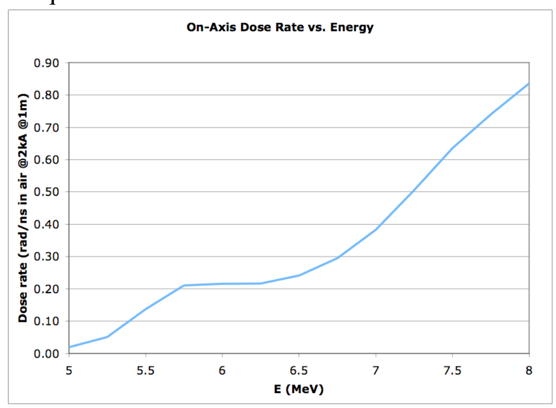

Figure 9. Dose rate versus energy for the nominal tune.

SUMMARY

We have performed beam transport simulations of a conceptual design for a compact 8 MV dielectric wall accelerator. The high accelerating gradient opens up a new regime of beam transport that relaxes many constraints on tune acceptance and focusing requirements. Coupling the beam transport results to Monte Carlo simulations of radiographic performance show that a DWA system can serve as a good x-ray source even without much optimization with respect to emittance growth.

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[3] Y-J. Chen, J. F. McCarrick, S. Nelson, "Transverse Beam Instability in a Compact Dielectric Wall Induction Accelerator,' FPAT035, this conference.

[4] J.F. McCarrick, "A Numerical Study of On-Axis Dose Rate from Ta and W Bremsstrahlung Converter Targets," release pending as a LLNL UCRL report.